U.S.NRC

UNITED STATES NUCLEAR REGULATORY COMMISSION

Protecting People and the Environment

Current Status of LOCA Cladding Criteria in the United States

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Recent Events

- In May 2008, the staff published a Research Information Letter (RIL-0801) containing the proposed technical basis.
- In June 2008, the staff published NUREG/CR-6967, which contains the supporting data from the testing program.
- The staff held a public workshop in September 2008.
- The staff discussed its technical basis conclusions with the Nuclear Regulatory Commission's Advisory Committee on Reactor Safeguards (ACRS) in December 2008.

Safety Assessment

- Results from the…research program indicate that fuel criteria…need to be revised and expanded...
- There is reasonable assurance that plant operations and public health are not challenged.
- Implementing these new requirements into the operating fleet may proceed on a reasonable schedule.

Plant Safety Assessment of RIL 0801
February 23, 2009 [ML090340073]

Scope of NRC's LOCA Research

Determine the effect of burnup on the embrittlement criteria in 10 CFR 50.46 and provide the technical basis for their revision.

2200ºF Peak Cladding Temperature Limit (no change needed)

17% Maximum Cladding Oxidation (effort focused on this)

Several other fuel-related LOCA phenomena are under investigation or consideration in the NRC's future research programs, but they are not needed at this time to revise the embrittlement criteria in the rule.

- Mechanical Behavior of Balloon
- Ballooning and Flow Blockage
- Axial Fuel Relocation into a Balloon
- Loss of Fuel Particles through a Rupture Opening

Completed NRC LOCA Research Projects

- Argonne National Laboratory – with irradiated material provided by the nuclear industry, NUREG/CR-6967
- Kurchatov Institute – funded jointly by NRC and IRSN (France) with additional funding from TVEL (Russia), NUREG/IA-0211
- Halden Reactor Project – bilateral project funded by NRC, IFE/KR/E-2008-004

Findings of RIL-0801

1. Regarding embrittlement, alloy composition effects were minor, but burnup effects were substantial.

2. Oxygen was found to enter the cladding from the inside as well as the outside of high-burnup fuel rods.

3. The formation of oxide on the surface of the cladding during a transient can break up and allow large amounts of hydrogen into the cladding.

4. If rupture occurs during a LOCA transient, large amounts of hydrogen can also enter the cladding from the inside near the rupture location.

Research Background

This research focused on the adequacy of the oxidation limit to prevent cladding embrittlement.

- Calculated cladding oxidation, which is a measure of time at temperature, is used as an indicator of embrittlement.
- Diffusion of oxygen into the metal (rather than oxide buildup on the surface) causes embrittlement.
- The cladding oxidation limit is very important because time at temperature (not temperature alone) determines embrittlement.

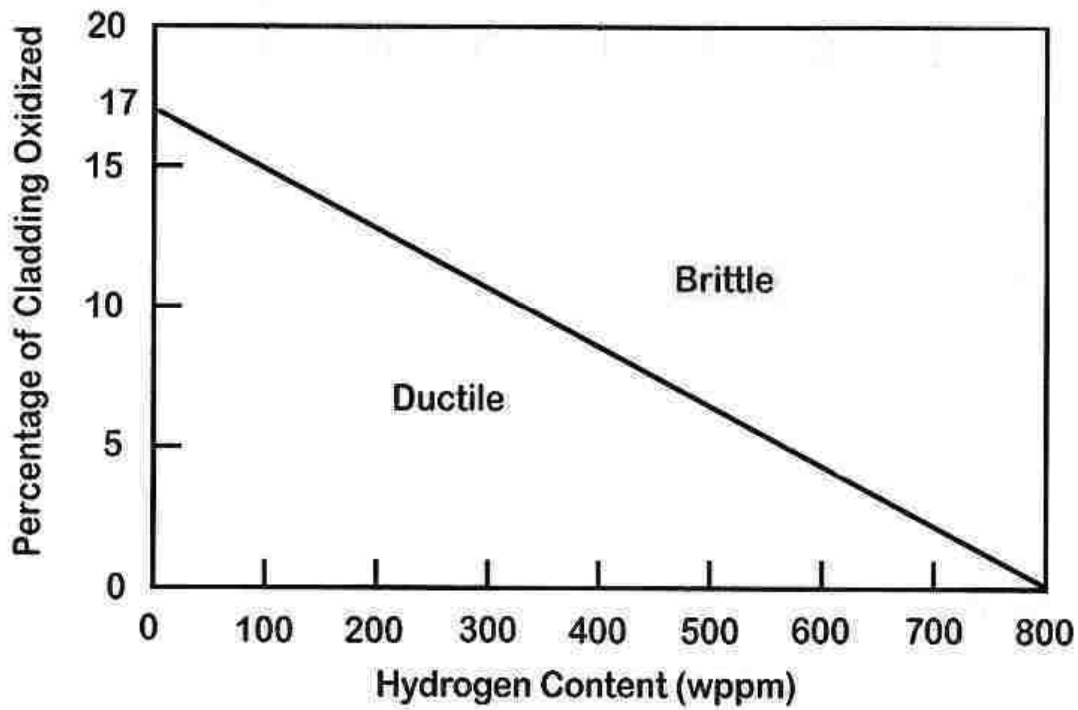
Research Finding #1

Burnup-related processes reduce the oxidation limit below 17%

- Hydrogen is absorbed in the cladding as a consequence of cladding corrosion during normal operation.
- Hydrogen accelerates the diffusion of oxygen in the cladding metal during a LOCA, thus speeding up embrittlement.
- Embrittlement during a LOCA therefore correlates with the hydrogen content from normal operation.

Research Finding #1

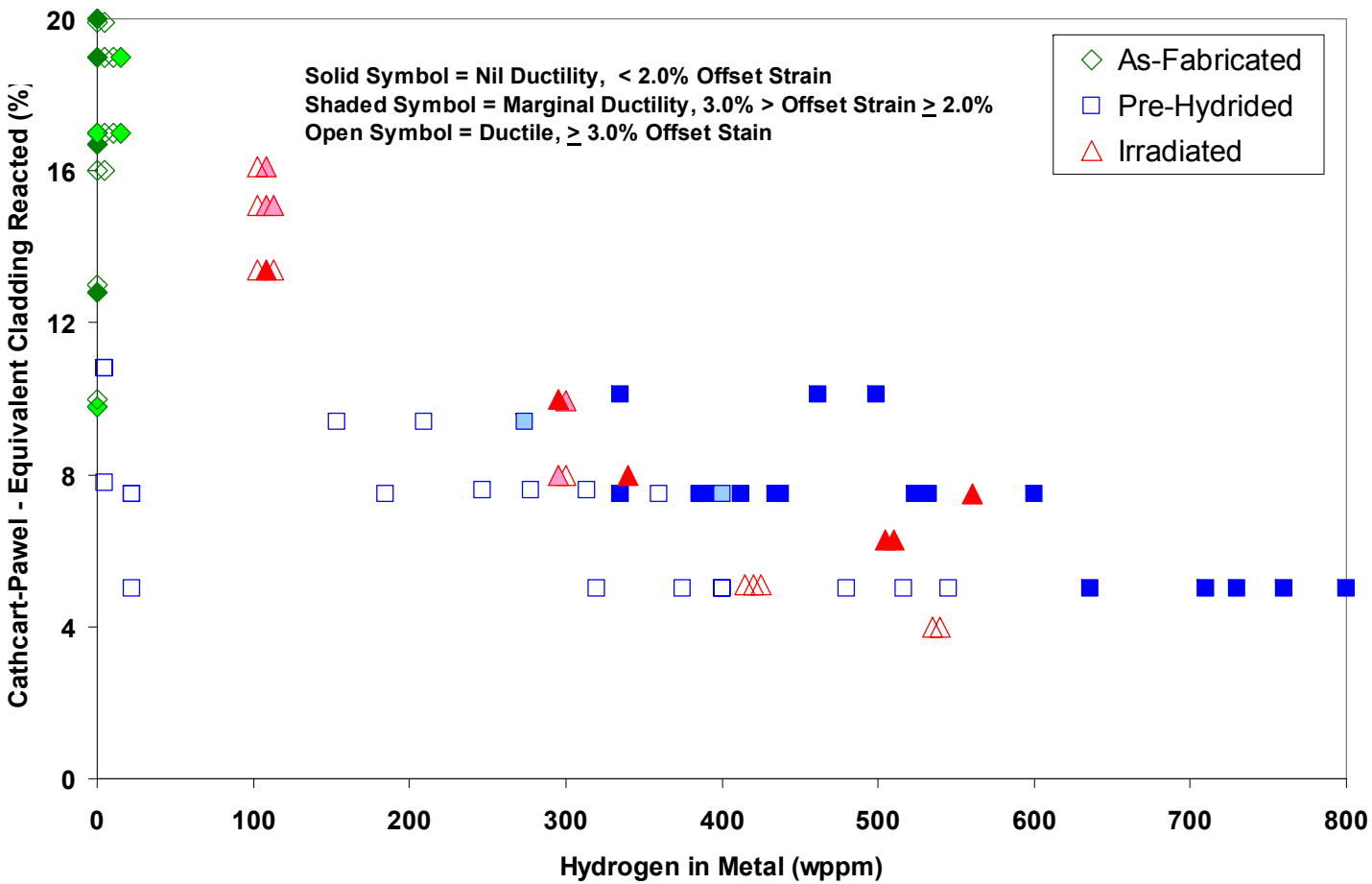
Burnup-related processes reduce the oxidation limit



General trend in allowable cladding oxidation versus pre-transient hydrogen content.

Research Finding #1

Embrittlement does not occur at a constant 17%



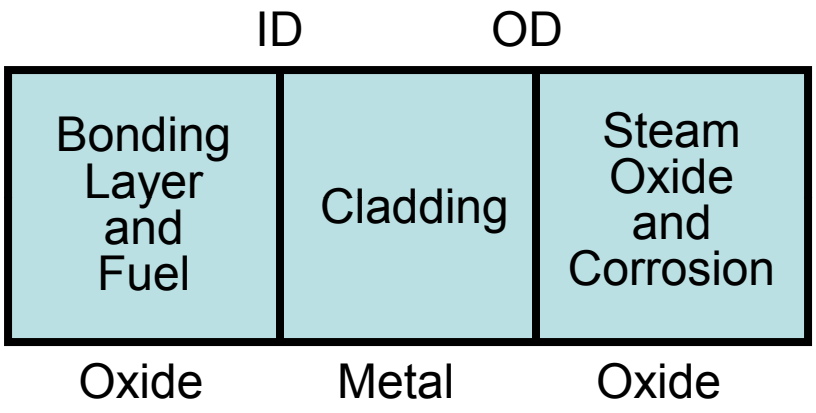
Research Finding #2

Oxygen can enter the cladding metal from the inside as well as the outside surface of high-burnup cladding.

- This can double the calculated oxidation in some analytical nodes
- Two-sided oxidation is already calculated in the rupture node so it may not create a more-limiting case
- ID oxygen pickup is not expected to occur in fresh fuel.

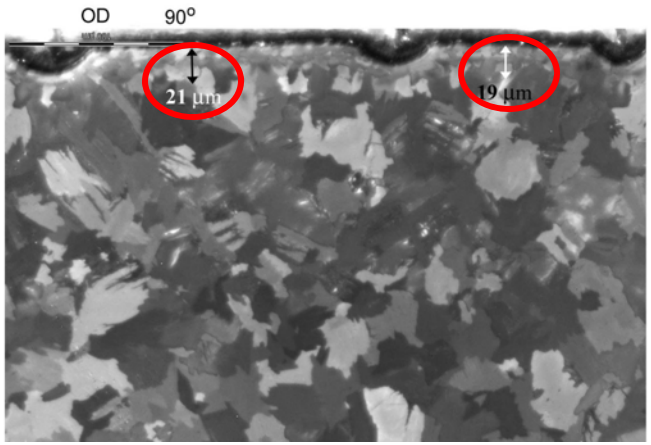
Research Finding #2

At high burnup, an oxygen source is present on both the inside and the outside of the cladding

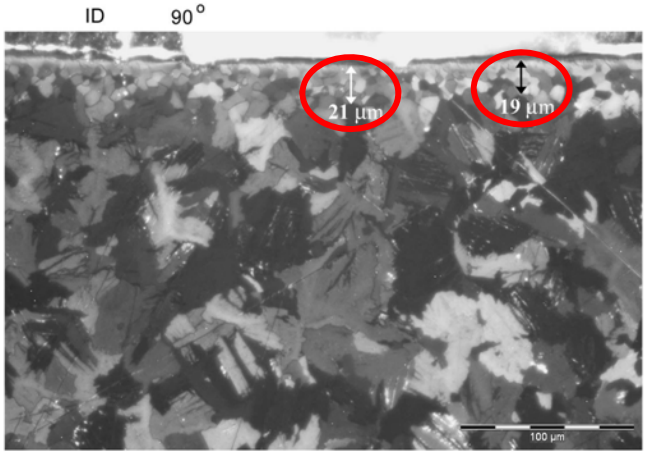


- Bonding of oxide pellet and cladding forms during normal operation.
- Nearly equal amounts of oxygen diffuse into cladding metal from the inside and the outside during a LOCA because cladding is approximately isothermal.

Research Finding #2



Outer Cladding Surface



Inner Cladding Surface

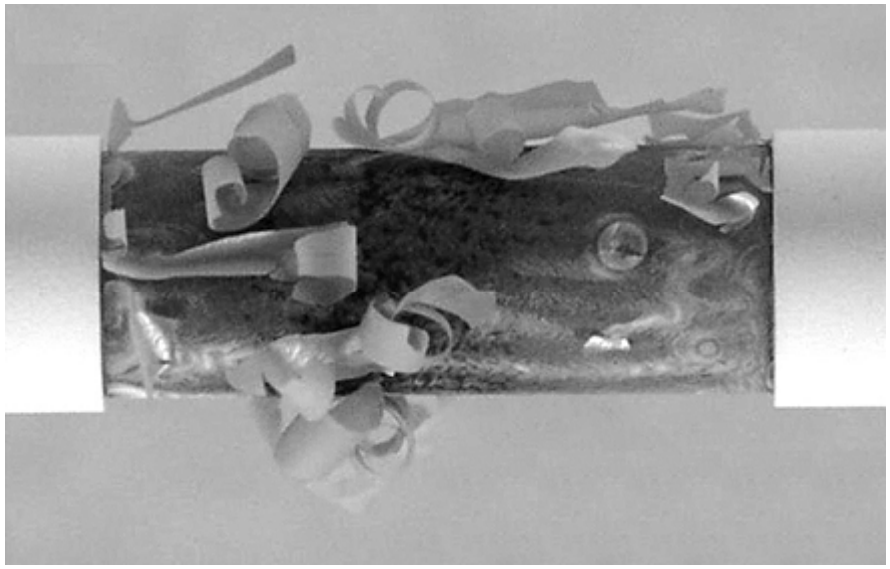
Micrographs of Halden LOCA test specimens indicating oxygen-stabilized layers on both inside and outside surfaces

Research Finding #3

Breakaway oxidation eventually occurs in all zirconium alloys and must be avoided because rapid embrittlement follows.

- Oxide crystal structure can change from tetragonal (protective) to monoclinic (cracked) in the LOCA temperature range.
- Breakaway is affected by surface finish and alloy impurities.
- Causal factors are not well known, so only way to make sure cladding has sufficient breakaway resistance is to test it.

Research Finding #3



Cladding sample that has experienced breakaway oxidation

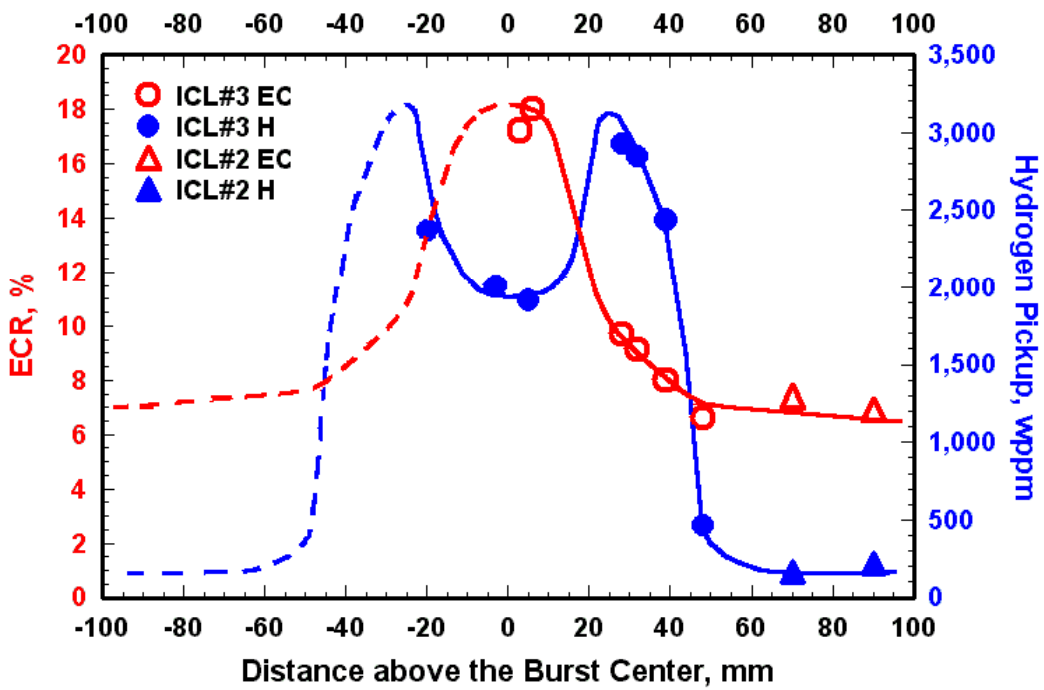
Research Finding #4

If rupture occurs during a LOCA transient:

- Oxidation of the inside cladding wall will occur near the rupture location
- Large amounts of hydrogen produced from the steam-cladding reaction can also enter the cladding inside surface
- Both observations confirm older findings

Research Finding #4

Oxygen and hydrogen in the rupture node



Axial distribution of oxygen and hydrogen based on measured and metallographic results

NUREG/CR-6967, Figure 229

Rulemaking Objectives

Following Commission directive, develop a rule which:

- Establishes appropriate safety margins for high-burnup fuel based on recent research results.
- Enables use of advanced cladding materials without exemptions.
- Permits replacement of prescriptive criteria with performance-based regulatory requirements.

Testing Essentials

Regulations provide revised cladding acceptance criteria

- Peak cladding temperature limit of 2200°F (1204°C).
- Local oxidation limit dependent on pre-transient hydrogen content.
- Inside surface oxidation from fuel-cladding bonding layer
- Breakaway oxidation limit

Vendor testing expectations:

- Periodic breakaway oxidation testing (200 wppm hydrogen)
- Data to support threshold for fuel-cladding bonding layer
- Applicability to new cladding alloys

Acceptable experimental procedures for post-quench ductility and breakaway oxidation to be described in a Regulatory Guide.

Optional testing

- Optional testing to define alternative criteria.

Rulemaking Process

Milestones	Dates
RIL-0801	✓MAY 2008
NUREG/CR-6967	✓ JUN 2008
FRN Soliciting Public Comment	✓ AUG 2008
Public Workshop #1	✓ SEP 2008
Assessment of Technical Basis	✓ DEC 2008
Advisory Committee on Reactor Safeguards (ACRS)	✓ DEC 2008
Additional research testing (PQD and breakaway)	✓ APR 2009
Comprehensive Test Procedures	✓ APR 2009
Advance Notice of Proposed Rulemaking (ANPR)	AUG 2009
Public Comment Period (75 days long)	
Public Workshop #2	
Backfit Determination per 10 CFR 50.109	
Proposed Rule	~ AUG 2010
ACRS	
Public Comment Period	
Final Rule	~ AUG 2011

Industry Issues

1. [NRC should not include] a cladding inner surface oxidation requirement without quantification of the phenomenon.

2. [NRC should not include] a periodic breakaway oxidation testing requirement when modern cladding alloys used in U. S. reactors show significant margin.

3. [The rulemaking effort should be deferred until] uncertainty in the final treatment of the embrittlement changes in the region of the clad that may balloon and burst during a LOCA [is resolved].

Nuclear Energy Institute letter to NRC dated April 9, 2009 (ML091000552)

Comment on Issues

1. **[NRC should not include] a cladding inner surface oxidation requirement without quantification of the phenomenon.**
   - *The phenomenon exists – the question is when it exists*
   - *Inner surface oxidation is already considered in the rupture node*

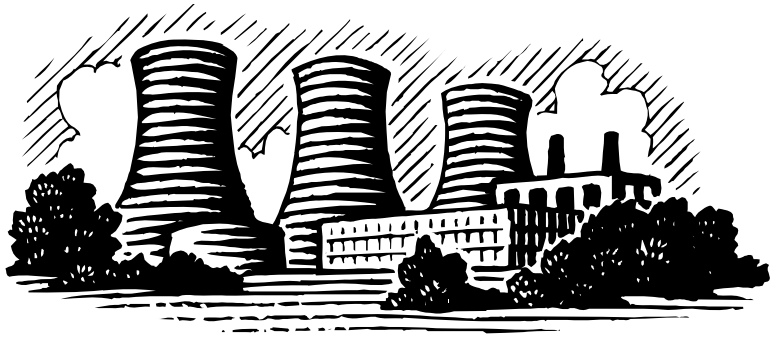
2. **[NRC should not include] a periodic breakaway oxidation testing requirement when modern cladding alloys used in U. S. reactors show significant margin.**
   - *All zirconium alloys exhibit breakaway after some period of time*
   - *Small changes in production result in large changes in performance*

3. **[The rulemaking effort should be deferred until] uncertainty in the final treatment of the embrittlement changes in the region of the clad that may balloon and burst during a LOCA [is resolved].**
   - *Regulatory issues with ballooning have existed for years.*
   - *Resolution of known non-conservatisms in embrittlement need not be delayed by continued uncertainties with ballooning.*

Conclusions

- In 1996, the NRC began a fuel cladding research program intended to investigate the behavior of high burnup fuel cladding under accident conditions.
- Empirical results and conclusions from this research program highlighted the need to pursue changes to the current U.S. criteria.
- NRC has outlined specific rule change objectives and developed strategies to address deficiencies in the current criteria.
- NRC is moving forward with revising the current U.S. cladding embrittlement criteria to ensure continued safe plant operation by appropriately accounting for new cladding embrittlement mechanisms and for expanded knowledge of previously identified mechanisms.

Closing

There is reasonable assurance that plant operations and public health are not challenged.

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